10/587234
IAP11 Rec'd PCT/PTO 24 JUL 2006

creases (demanded by the cooling system at the suction valve of the linear compressor), this means that a thermal load has been put into the cooler. This warmer mass raises the temperature of the internal environment of the cooling system, causing the rise in the evaporation pressure, since the cooling liquid is in a saturated liquid state, and one can conclude that the pressure and the temperature are intrinsically interconnected. Thus, the fact of placing something warmer in the cooler, will result in a rise in pressure, raising the pressure of the gas on the piston, causing the resonance of the mechanism to decrease, which will cause a phase shift in the linear compressor.

In practice, this means that, as the heat inside the cooler rises, the load of the system also rises, causing the resonance frequency of the system to rise, and the piston stroke should be increased, which results in reducing of resonance frequency, since the piston stroke is longer. In this case, that difference by which the resonance frequency has risen as a function of the load added to the system, may cause the system to operate again at the previous frequency (or resonance frequency), increasing the piston displacement, leading the assembly to operate in resonance frequency.

On the other hand, a decrease in the load of the system (frozen food, lowering the ambient temperature) leads to an increase in the system phase, which may render the phase positive and compensate with a decrease in the system capacity until the phase reaches the zero value.

In this way, while the phase shift is positive, one should decrease the cooler capacity, to have the system operating again in resonance and, when the phase shift is negative, the capacity of the linear compressor should be increased, to have the system operating again in resonance.

One of the objectives of the present invention is achieved by means of a linear motor comprising a stator and an actuator, the stator being fed by a controlled voltage, the controlled voltage being applied to the linear motor and adjusted by a processing unit by means of a variable frequency inverter, the linear motor having a voltage frequency, the linear motor moving a load from the actuator displacement, the linear motor forming a resonant

assembly with the load, the resonant assembly having a resonance frequency, the processing unit is configured to control a displacement range of the actuator by means of the controlled voltage, the processing unit selectively increasing or decreasing the displacement range in a proportional manner to the variations of the resonance frequency throughout the load variations and to dynamically keep the resonant assembly in resonance.

Further, one of the objectives of the present invention is achieved by means of a linear compressor applicable to a cooling system, the linear compressor comprising a piston driven by a linear motor, the piston having a displacement range controlled by a controlled electric voltage, the controlled electric voltage having a voltage frequency applied to the linear motor and adjusted by a processing unit, the processing unit being configured to dynamically control the range of piston displacement as a function of the variable demand of the cooling system, the linear compressor having a resonance frequency, the processing unit adjusting the range of piston displacement so that the linear compressor will be dynamically kept in resonance throughout the variations in demand of the cooling system, the control of the pistons displacement being made by means of the controlled voltage that is adjusted by means of a variable frequency inverter, the inverter dynamically adjusting the voltage frequency of the controlled voltage to a value equal to the value of the resonance frequency of the linear compressor, as the variations in demand of the cooling system occur.

The objectives of the present invention are also achieved by means of a method of controlling a linear compressor, the linear compressor comprising a piston driven by a linear motor, the linear motor being fed by a controlled voltage having a voltage frequency of the linear motor and generating a capacity of the linear compressor, the method comprises the following steps of: measuring the feed frequency of the linear motor and compensating the feed frequency by comparing the measurement with a reference frequency and increasing the capacity if the linear compressor if the voltage frequency is higher than the reference frequency, or decreasing the capacity if the linear compressor if the voltage frequency is lower than the reference

frequency.

Further, the objectives of the present invention are achieved by means of a method of controlling a linear compressor, which comprises steps of measuring a feed phase of the feed current and a dynamic phase of the piston of the linear compressor, and measuring and establishing a measured phase, and dynamically adjusting the displacement range as a function of a variation in the demand of the linear compressor, so that the linear compressor will be kept in resonance throughout the variations in the demand of the cooling system so that the value of the measured phase will be null.

The teachings of the present invention are further carried out by means of a cooling system comprising a linear compressor, the cooling system comprising an on/off thermostat actuating the linear compressor, a linear compressor comprising a piston driven by a linear motor a piston having a displacement range controlled by means of a controlled voltage, the controlled voltage having a voltage frequency applied to the linear motor and adjusted by a processing unit, the range of piston displacement being dynamically controlled in junction of a variable demand of the cooling system during the period when the thermostat turns on the linear compressor, the linear compressor having a resonance frequency, the processing unit adjusting the range of piston displacement so that the linear compressor will be dynamically kept in resonance throughout the variations in demand of the cooling system, the displacement being adjusted through the controlled voltage by means of a variable frequency inverter, the inverter dynamically adjusting the voltage frequency of the controlled voltage to a value equal to the resonance frequency of the linear compressor, as the variations in demand of the cooling system occur.

Brief Description of the Drawings

The present invention will now be described in greater detail with reference to embodiments represented in the drawings. The figures show:

- Figure 1 is a schematic view of a linear compressor;

- Figure 2 is a diagram of the control system, of the linear compressor and of the cooling system of the present invention;

- Figure 3 is a block diagram of the control system, the linear compressor and the cooling system, illustrating the use with a conventional thermostat;

- Figure 4 is a block diagram of the control system of the present invention;

- Figure 5 is a block diagram of the algorithm of automatic control of the capacity applicable to the linear compressor and the cooling system of the present invention;

- Figure 6 represents a curve of the load of the electric motor in function of the phase;

- Figure 7 represents a curve of the capacity of the electric motor in function of the phase for various loads;

- Figure 8 is a time diagram illustrating the wave forms of the voltage network, counter-electromotive force (CEMF), current of the electric motor, position of the piston and signal of the sensor in the situation in which the linear compressor is operating at the resonance ($\phi_{PC} = \phi_P - \phi_C = 0$);

- Figure 9 is a time diagram illustrating the wave forms of the voltage network, counter-electromotive force (CEMF), current of the electric motor, position of the piston and signal of the sensor in the situation in which the linear compressor is operating above the resonance ($\phi_{PC} = \phi_P - \phi_C > 0$);

- Figure 10 is a time diagram illustrating the wave forms of the network voltage, counter-electromotive force (CEMF), current of the electric motor, position of the piston and signal of the sensor in the situation in which the linear compressor is operating below the resonance ($\phi_{PC} = \phi_P - \phi_C < 0$);

- Figure 11 is a flow diagram of the method for controlling the linear compressor of the present invention;

- Figure 12 represents a curve of the load of the electric motor in function of the phase, when the teachings of the present invention are employed, according to a second preferred embodiment;

- Figure 13 represents a curve of the capacity of the electric motor in function of the phase for various loads when the teachings of the present invention are employed, according to a second preferred embodiment;

and

- Figure 14 represents a flow diagram of the method for controlling the linear compressor, according to a second embodiment of the present invention.

Detailed Description of the Figures

As can be seen, Figure 2 illustrates a system comprising a cooler/refrigerator with the embarked electronics. In this case, an electronic thermostat 25 is integrated into the cooling system 20 and supplies a reference signal for the processing unit 22. The processing unit 22, in turn, controls the linear compressor 100, receiving a signal from the sensor SS corresponding to the displacement of the piston 1.

Electronic Controls

Figure 3 illustrates a cooling system 20 applied to a simple-class cooler. As can be seen, in this case, the cooling system 20 supplies only a signal that turn the processing unit 22 on and off. In this way, the cooling system 20 can dispense all the electronics foreseen in the coolers/cooling systems that comprise embarked electronics. Moreover, with this construction the processing unit 22 can be integrated to the linear compressor 100 (see indication 31), which may be supplied for various coolers/refrigerator/cooling systems 20 manufacturers, resulting in an equipment with high flexibility when compared with pieces of equipment of the prior art. A proximity sensor 30 associated to the processing unit 22 will provide the position of the piston 1 when the latter comes close to the respective stroke end. In practice, minor variations in the piston stroke correspond to great variations in the capacity of the linear compressor, so that, by way of example, for a maximum stroke of 8.5 mm (maximum capacity) the minimum stroke would be about 6.5 mm (capacity close to zero), that is, about 2 mm of stroke variation range for the capacity to vary from zero to the maximum.

Figure 4 illustrates a detail of the processing unit 22. As can be seen, the processing unit 22 comprises a microcontroller 40, which controls a TRIAC 41 through a gate 42. The microcontroller 40 receives the signals of detection of zero of the network V_{AC} voltage ZT, as well as the zero signal of

the current ZC at the exit of the TRIAC 41. A displacement reference signal REF may be supplied by the cooler, if a cooler with embarked electronics is used. The main signal for the present invention refers to the displacement signal DP, which is obtained from the signal SS of the proximity sensor 30 and that should be treated, for instance, according to the teachings of Brazilian patent document PI 0301969-1, the description of which is incorporated herein by reference. Optionally, one may use the value of the feed current i_A at a moment different from ZC; for this purpose, one should make the necessary adjustments in order to have the correct measurements.

Control Algorithm

Figure 5 illustrates the algorithm according to a first embodiment of the present invention for obtaining the controlled voltage V_M that should be applied to the linear motor 10, so that one can keep the linear compressor 100 in resonance. As can be seen, in order to calculate the value of the controlled voltage V_M, it is necessary to calculate a measured phase ϕ_{PC}, which is obtained from the difference between the dynamic phase ϕ_P and the current feed phase ϕ_C:

$$\phi_{PC} = \phi_P - \phi_C$$

The calculation of the current phase or feed phase ϕ_C is made from the zero of the current ZC and from the zero voltage zero ZT, whereas the calculation of the piston-displacement phase or dynamic phase ϕ_P is made from the piston-displacement signal DP and from the zero of the voltage ZT.

Further with respect to the obtention of the feed phase ϕ_C, the feed current i_A may not have a passage by zero, which would make it possible to capture a pre-defined moment for establishing the zero of the current ZC. This may be observed, for instance, in Figures 8, 9 and 10, where the feed current i_A remains at zero for a certain period. In this case, one should consider the pre-defined moment as the average point of permanence of the feed current i_A at zero.

From the values of the dynamic phase ϕ_P and the feed phase ϕ_C, one can obtain the value of the measured phase ϕ_{PC} and obtain the reference value of the maximum piston displacement DP_{REF} (displacement that one expects to achieve a defined physical position). This value may be obtained by means of the algorithm of Figure 11.

Once the reference value of maximum piston displacement DP_{REF} has been obtained, it is sufficient to subtract from it the maximum piston displacement DP_{MAX} by the equation:

$$E_{DP} = DP_{REF} - DP_{MAX}$$

to obtain the error value E_{DP} between reference maximum piston displacement DP_{REF} and the maximum of piston displacement DP_{MAX}.

From this result it is possible to obtain the value of a control voltage V_P, since its value is a function of the error E_{DP}. This relationship may be observed in the flow diagram in figure 11. Therein one may change increasing capacity with increasing DP_{REF}, and may change decreasing capacity with decreasing DP_{REF}. Alternatively, one may also use, for instance, a traditional method such as a PID algorithm to alter DP_{REF}; in this case, the calculation would be made from the following equation:

$$DP_{REF} = K_P \times \phi_{PC} + K_D \times \left(\frac{\partial \phi_{PC}}{\partial T} \right) + Ki \times \int \phi_{PC} \times \partial T$$

wherein K_P is a proportional constant, KD is a derived constant and Ki is an integral constant, as known from the classic nomenclature in control.

Further one may directly increase or decrease the value of the control voltage V_P, since this value if a function of ϕ_{PC}. In this case, in the flow chart of Figure 11, one may change increasing capacity with increasing V_P, and may change decreasing capacity with decreasing V_P, so that in this option one may also use some traditional method such as PID algorithm to alter V_P from ϕ_{PC} by using the following equation:

$$V_P = K_P \times \phi_{PC} + K_D \times \left(\frac{\partial \phi_{PC}}{\partial t} \right) + Ki \times \int \phi_{PC} \times \partial t$$

The constants are the same as described before.

From the value of the control voltage V_P it is possible to adjust the controlled voltage V_M by calculating the trigger angle of the TRIAC.

According to the graph of Figures 6 and 7, increases in the system load (increase in room temperature, increase in the thermal load in the system) lead to a decrease in the system phase. If this increase in the load is large (see dashed line with indication of "maximum load" in Figure 7) the phase will go on to negative values; this can be compensated by an increase in the capacity of the system (increase in the piston stroke 1), which will increase the phase, so that successive increments in the capacity lead the phase to the zero value, that is to say, the system will be operating in resonance. In an equivalent way, a decrease in the load (see dashed line with indication of "minimum load" in Figure 7) the phase will go to positive values, and this variation can be compensated by an increase in phase, so that successive increments lead the value of the phase to zero, that is to say, the system will be operating in resonance.

As far as the manner of making the increase and the decrease in phase is concerned, the reading of the feed phase ϕ_C and the dynamic phase ϕ_P every cycle or semi-cycle should be foreseen. So, whenever the measured phase ϕ_{PC} is different from zero, the control system should actuate on the piston displacement, and the reading of the dynamic phase ϕ_{PC} may be made according to the teachings of Brazilian patent document PI 0300010-9, which is incorporated herein by reference.

The amplitude of the decrements should take into consideration the reaction of the system in response to the increment/decrement caused by the control system. Thus, if the value of the increment/decrement is high, a longer stabilization time will be required; in the contrary case, the stabilization time will be shorter. Typically, the stabilization time depends upon the constants of the compressor time and of the cooling system. By way of example,

one may opt for awaiting a predetermined time, for instance about 10 to 60 seconds, or monitor the system phase until the latter remains constant.

Optionally, it is possible to use variable increment/decrement values. In this case, if the measured phase ϕ_{PC} is large, one may use larger increments/decrements, and decrease this value as the value of the measured phase ϕ_{PC} comes close to zero. In this case, one may opt for a reference value of 1% of increment/decrement.

Figure 8 shows a time diagram illustrating the wave forms of voltage of the network V_{AC} of the counter-electromotive force (CEMF), of the current i_A of the linear motor 10, of the piston position DP and of the signal of the proximity sensor (not shown) in the situation where the linear compressor 100 is operating in resonance, that is to say, when $\phi_{PC} = \phi_P - \phi_C = 0$.

As can be seen, in the situation of resonance, the piston displacement is maximum when the feed current i_A of the linear motor 10 passes by zero, a moment when the proximity sensor shows a measurable signal (see indication 80). In this condition, linear compressor 100 operates in optimum condition, since in this case the feed current i_A passes by zero at the moment when the piston 1 is changing direction in its path, that is to say, it passes by a moment of maximum displacement, when there is no need for application of force onto it, since when the piston 1 is at mid-displacement (see indication 82) the feed current i_A and the CEMF are maximum, impelling the piston 1 in the most effective way possible.

In Figure 9 one can observe that the linear compressor 100 is operating above the resonance, that is to say, the CEMF is in delay with respect to the feed current i_A of the linear motor 10. In this case, the equation is $\phi_{PC} = \phi_P - \phi_C > 0$, and one should increment the capacity of the linear compressor 100 by raising the controlled voltage V_M. It can be noted that, in this situation, when the piston 1 is at maximum displacement of its path, a moment when no feed current i_A should be applied to the linear motor 10, the feed current i_A already has a significant value at this moment. According to the same situation of phase shift, at the moment when the piston 1 is at the middle of its path (see indication 90), a moment when the maximum feed cur-

rent i_A should be applied to the linear motor 10, the feed current i_A has already undergone a decrease in its level, so that in the two situations there is a waste of energy and, therefore, a reduced efficiency in the operation of the linear compressor 100 as a whole.

In Figure 10 one can observe that the linear compressor is operating below the resonance; in this case the CEMF is advanced with respect to the feed current i_A of the linear motor 10, and the equation is then $\phi_{PC} = \phi_P - \phi_C < 0$. In this case, one should increment the capacity of the linear compressor 100, to have the system operating in resonance.

As can be seen, in this situation there is a delay in the phases, which causes the linear compressor to operate with low efficacy, since at the moment when the piston displacement is maximum, a situation on which no feed current i_A should be applied to the linear motor 10, one can observe that the feed current i_A is not null. Moreover, at the moment when the piston 1 is at the middle of the displacement (see indication 101), a moment when a maximum of feed current i_A should be applied to the linear motor 10, the feed current i_A is not maximum, so that, in this case too, the linear compressor 100 has its efficiency reduced.

<u>Application in Linear Compressors</u>

Structurally, the linear compressor 100 and the system of controlling a linear compressor 100 have the following characteristics:

The linear compressor 100 comprises a piston 1 and is driven by the linear motor 10, which brings about a displacement range that will be controlled through the controlled voltage V_M, this controlled voltage V_M having a voltage frequency f_P. The range of piston 1 displacement is dynamically controlled as a function of the variable demand of the cooling system 20, through the processing unit 22, which adjusts the range of piston displacement, so that the linear compressor 100 will be dynamically kept in resonance throughout the variations in demand of the cooling system 20, that is to say, so that its displacement range will be adjusted throughout the changes resulting from the variations in load demanded by the cooling system 20, impelling the linear compressor to operate in resonance. The system

of controlling the linear compressor 100, when taken in isolation, should be applicable to the linear compressor so as to make the dynamic adjustment of the displacement range, to have the linear compressor operating in resonance.

Application in Cooling Systems

The cooling system 20, which may include a cooler/refrigerator or an air-conditioning system and analogous systems, as already commented, should comprise an on/off thermostat actuated by the linear compressor 100, to have the range of piston displacement dynamically controlled as a function of the variable demand of the cooling system 20 during the period when the thermostat turns on the linear compressor. The processing unit 22 should dynamically adjust the range of piston displacement, so to keep the linear compressor in resonance throughout the variations of demand of the cooling system 20.

In order to control the linear compressor 100, the control system and the cooling system 20 of the present invention are provided with a method of controlling the linear compressor 100 that follows the flow chart illustrated in Figure 11.

The control over the range of piston 1 displacement is made by means of a controlled voltage V_M, which is adjusted by the processing unit 22. In order to adjust the level of the controlled voltage V_M, one may opt for following the teachings of a brazilin patent document PI 9907432-0, which is incorporated herein by reference.

Application in Linear motors

Bearing in mind that, with a control usable on linear compressors in general, one can make use of the teachings of the present invention on a linear motor 10 applied to other types of utilization. In this case, an actuator (not shown) has the same function of the piston 1 used in the compressor 100, that is to say, the actuator receives the force generated at the stator 411, moving the load and forming a resonant assembly that will have a resonance frequency.

In an analogous way as foreseen for the control over the linear

compressor 100, the actuator has a displacement range that will be controlled by means of the controlled voltage V_M from the processing unit 22, so that the resonant assembly will be dynamically kept in resonance throughout the variations of load.

The control over the linear motor 10 may also be made by means of the processing unit 22, which measures the feed phase ϕ_C of the feed current i_A and of the dynamic phase ϕ_P, in this case of the actuator rather than of the piston, and adjusts the controlled voltage V_M, so that the value of the measured phase ϕ_{PC} will be null.

Also, one may control the linear motor 10 by using a variable frequency inverter, which should be dynamically adjusted to the voltage frequency f_{VM} of the controlled voltage V_M to a value equal to the value of the resonance frequency of the resonant assembly, as the load variations occur.

Control Method by Phase Adjustment

In order to carry out the control method, the processing unit 22 monitors the range of piston 1 displacement throughout the operation of the linear compressor 100 and dynamically adjusts the displacement range as a function of a variation in demand of the linear compressor 100, so that the linear compressor 100 will be kept in resonance throughout the variations in demand of the cooling system 20.

In order to impel the linear compressor 100 to operate in resonance, one measures the feed phase ϕ_C of a feed current i_A and the dynamic phase ϕ_P of the piston 1 of the linear compressor 100 and measures the difference between the measured phases to establish the measured phase ϕ_{PC}.

After the step of establishing the measured phase ϕ_{PC}, one should increment the range of piston 1 displacement when the value of the measured phase ϕ_{PC} is positive or a step of decreasing the range of piston 1 displacement when the value of the measured phase ϕ_{PC} is negative, and one should always increase or decrease the displacement of the piston 1 to a value necessary for the measured phase ϕ_{PC} to be null.

By preference, after the step of increasing or decreasing the range of piston 1 displacement, one should wait until a stabilization time has

passed before measuring again the difference between the feed phase ϕ_C and the dynamic phase ϕ_P.

Control Method by Adjustment of Phase Frequency

According to a second preferred embodiment of the present invention, another way of controlling the compressor to control the frequency applied to the motor to keep it will always operating in resonance.

In this case, the control is made through the variable frequency, by using a variable frequency inverter (not shown). In this way, when the load applied to the linear compressor 100 is changed, there will also be a change on the dynamic phase ϕ_P of the system, which will be detected by the control system of the present invention, in order to alter the frequency for the compressor to operate in resonance. This control is dynamically made by adjusting the voltage frequency f_{VP}, through the variable frequency inverter, to a value equal to the resonance frequency of the linear compressor 100, as the variations in demand of the cooling system 20 occur.

The ways of making this kind of adjustment may include, for example, varying the frequency so as to minimize the feed current or else varying the frequency so as to zero the phase between current and the CEMF.

As can be seen in Figures 12 and 13, when the load increases, the frequency of the linear compressor 100 increases, and one should increment the respective capacity, to have the system operating in resonance and vice-versa, when the load decreases, that is to say, the system should increase the piston 1 stroke/capacity/compressor 100 and, when the frequency decreases, the control system should decrease the stroke/capacity. In the same way as in the first preferred embodiment of the present invention, it is possible to operate the cooling system by means of a simple "On/Off"-type thermostat, maintaining the same concept of adjustment of the piston 1 (capacity of the compressor 100) by varying the frequency.

In this regard, one can observe that the basic concept between the first preferred embodiment of the present invention and the second embodiment is similar, that is to say, one can observe the effect of the change in the load applied to the compressor with respect to the resonance frequency,

and, with this information, alter the piston stroke (compressor capacity).

With the control method in this embodiment, one can proceed in accordance with the flow diagram shown in Figure 14 and following these steps:

measuring the feed frequency of the linear motor 10, which is the voltage frequency f_{VP}, and then making the compensation of this measurement with the value of a reference frequency FR, which is usually of 50 or 60 Hz.

In this compensation step, if the voltage frequency f_{VP} is higher than the reference frequency FR, one should increment the capacity of the linear compressor 100. If the voltage frequency f_{VP} is lower than the reference frequency FR, one should decrease the capacity of the linear compressor 100.

To have these methods of the first and second embodiment operating in the best possible condition for the system, the linear compressor 100 has to be designed to operate in resonance when the system is stabilized and at low capacity (in this condition, the system should operate 80% of the time). In this way, when a greater capacity is necessary, the algorithm will increase the capacity of the linear compressor 100.

Another ability which the algorithm should have is the function of maximum (rapid) freezing. In a freezer, when this function is active, the linear compressor 100 will function for 24 hours without cycling; in systems with variable capacity, the linear compressor should function at the maximum capacity, regardless of the load or internal temperature. In order to perform this function, the algorithm may measure the cycle time, if this time is longer than a reference (for instance, 2 hours); the algorithm will go to the maximum capacity independently of the phase condition and will only operate normally again when the system cycles or when the 24 hours have passed.

<u>The advantages of the proposed solution are as follows</u>:

- it enables one to apply the linear compressor in simple systems, equipped with conventional thermostat and to use the advantages of the variable capacity;

- it reduces costs of the cooling/refrigerator system 20;
- it optimizes the functioning of the linear compressor (the linear compressor always works at the maximum efficiency);
- the performance of the linear compressor is improved;
- there is a correction in the pumping capacity of the linear compressor, adapted to the need of the cooling system 20.

Examples of preferred embodiments having been described, one should understand that the scope of the present invention embraces other possible variations, being limited only by the contents of the accompanying claims, which include the possible equivalents.